# Implications of the Diffuse Galactic Continuum

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**Abstract.** Observations made with *Ginga*, *OSSE* and *COMPTEL* provide evidence that the diffuse Galactic continuum emission extends down to $\sim$ 10 keV, and that the spectrum steepens below about several hundred keV. If this emission is electron bremsstrahlung, then a very large power ($\sim 10^{43}$ erg s$^{-1}$) is required to maintain the electrons against energy losses to the interstellar medium. This exceeds by an order of magnitude the total power provided by Galactic supernovae. We suggest that this power might be derived from the gravitational potential released on the passage of the ISM through Galactic spiral arm compressions. Alternatively, the hard X-ray Galactic continuum could be the superposition of unresolved point sources such as accreting neutron stars or black holes.

**Key words:** Gamma Rays: observations – ISM: cosmic rays

## 1. Introduction

Recent observations with various instruments operating in the hard X-ray through soft gamma ray regime confirm that the continuum emission of the Galaxy extends down to hard X-ray energies (Claret et al. 1994; Strong et al. 1994; 1995; Kurfess 1995; Purcell et al. 1996; Yamasaki et al. 1996a; 1996b). In an analysis of the *OSSE* observations (Kurfess 1995; Purcell et al. 1996) it has been demonstrated that, when the contributions from the point sources close to the Galactic center simultaneously observed with *SIGMA* are subtracted, the remaining *OSSE* flux from the direction of the Galactic center is essentially identical to the *OSSE* flux from the Galactic plane at $\ell = 25°$ and $\ell = 339°$. Hence this emission is probably of diffuse origin and its spatial distribution is essentially flat over the central radian in Galactic longitude.

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Furthermore, the spectrum of this emission steepens below a few hundred keV. If this emission is bremsstrahlung then a power of $\sim 10^{43}$ erg s$^{-1}$ is required to maintain these electrons against Coulomb losses in the ISM. This exceeds earlier estimates (Chi & Wolfendale 1991; Skibo & Ramaty 1993) by nearly two orders of magnitude. This is largely the result of the *Ginga* data (Yamasaki et al. 1996a; 1996b) which provide evidence that the steep power law spectrum (photon index -2.5) derived from the *OSSE* data in the 50 - 500 keV energy band extends down to $\sim$ 10 keV.

To assess the energetics of the low energy cosmic ray electrons we restrict our analysis to electrons with energies below about 50 MeV. At these energies electrons are stopped in the Galaxy predominantly through Coulomb collisions with a small fraction of their energy going into bremsstrahlung. Hence, the Galaxy is effectively an electron calorimeter. We calculate the power going into low energy cosmic ray electrons directly from the X-ray and gamma ray observations. The result is not very sensitive to the spatial distribution of the electrons.

## 2. Galactic Electron and Photon Spectra

In a thick target the photon production rate per unit photon energy is related to the electron injection rate per unit electron kinetic energy through

$$\frac{dN_\gamma}{dt\,d\epsilon}(\epsilon) = \int_\epsilon^\infty dE\, \frac{d\sigma_{brem}}{d\epsilon}(E,\epsilon)\, v\, n_g$$
$$\times \frac{1}{\left|\frac{dE}{dt}(E)\right|} \int_E^\infty dE'\, \frac{dN_e}{dt\,dE}(E'). \qquad (1)$$

Here $\epsilon$ is the photon energy, $v$ and $E$ are the electron velocity and kinetic energy, $n_g$ is the density of interstellar gas, $\left|\frac{dE}{dt}(E)\right|$ is the electron energy loss rate, and $\frac{d\sigma_{brem}}{d\epsilon}(E,\epsilon)$ is the differential bremsstrahlung cross section. For *ep* and *ee* bremsstrahlung we use the expressions given by Koch & Motz (1959) and Haug (1975), respec-

tively. We take into account the presence of Helium with abundance $n_{He}/n_H = 1/10$.

It is of central importance to point out that bremsstrahlung production in a thick target is independent of the density of the medium. This is because the energy loss rate is proportional to $n_g$ and only the product $\frac{1}{n_g}\left|\frac{dE}{dt}(E)\right|$ enters into equation (1). For the energy loss rate due to Coulomb collisions in neutral hydrogen we use (e.g. Longair 1992)

$$\frac{1}{n_{HI}}\left|\frac{dE}{dt}(E)\right|_{HI}^{coul} = \frac{2\pi e^4}{m_e c\beta}\left[\ln\left(1.38\times10^9\gamma^2\beta^2 E\right) + \frac{1}{\gamma^2}\right.$$
$$\left. - \left(\frac{2}{\gamma} - \frac{1}{\gamma^2}\right)\ln 2 + \frac{1}{8}\left(1 - \frac{1}{\gamma}\right)^2\right]. \quad (2)$$

In ionized hydrogen we use (Melrose 1980)

$$\frac{1}{n_{HII}}\left|\frac{dE}{dt}(E)\right|_{HII}^{coul} = \frac{4\pi e^4}{m_e c\beta}\ln\Lambda_c, \quad (3)$$

where we set $\ln\Lambda_c \simeq 23$ for the Coulomb logarithm. For bremsstrahlung losses we use (e.g. Ginzburg & Syrovatskii 1964)

$$\frac{1}{n_{HI}}\left|\frac{dE}{dt}(E)\right|_{HI}^{brem} = 3.71\times10^{-16}\,\beta\gamma \quad (4)$$

and

$$\frac{1}{n_{HII}}\left|\frac{dE}{dt}(E)\right|_{HII}^{brem} = 7.0\times10^{-17}\,(\ln\gamma + 0.36)\,\beta\gamma \quad (5)$$

in units of $(\text{MeV s}^{-1}\text{ cm}^3)$. These expressions are summed weighted by the ionization fraction $x \equiv n_e/(n_{HI} + n_{HII})$. We adopt an ionization fraction $x = 0.047$ derived from the parameters of the three component model of the ISM (Mckee & Ostriker 1977).

In Fig. 1 we show a compilation of the continuum fluxes integrated over latitude and the central radian in longitude of the Galaxy. Above 1 MeV measurements with *COMPTEL* reveal a spectrum which is a smooth extrapolation of the higher energy continuum measured with *COS-B* (Strong et al. 1994; 1995). The photon spectral index, although not very well constrained, is approximately -2. However, below 1 MeV the situation is somewhat different. The *OSSE* data show that the spectrum of the Galactic continuum steepens below a few hundred keV. Furthermore, the *Ginga* spectrum does not display a thermal cut off indicating that the steep nonthermal Galactic continuum extends to energies $\lesssim$ 10 keV (Yamasaki et al. 1996a, 1996b).

Using equation (1) with the energy losses given by equations (2)-(5), we find that an electron source spectrum given by

$$\frac{dN_e}{dt\,dE}(E) = 1.2\times10^{44}g\,\left(E^{-2} + 50\,E^{-3.7}\right)$$
$$(\text{electrons s}^{-1}\text{ MeV}^{-1}) \quad (6)$$

results in thick target bremsstrahlung emission with a spectrum that turns up appropriately. In Fig. 1 the solid curve is the calculated photon spectrum where, in addition to bremsstrahlung, we have added the contribution of inverse Compton emission (dotted curve) produced by higher energy ($\gtrsim$ GeV) electrons (Skibo 1993). Scaling from the central radian flux to the global quantity $dN_\gamma/dt\,d\epsilon$ requires multiplying by the factor $10^{46}g$ where $g$ is of order unity and only weakly depends on the unknown Galactic spatial distribution of the emission. For example, if the emission is confined to a point source at the Galactic center ($R_\odot = 8$ kpc), then $g = 0.77$, whereas if the emission is as broadly distributed as the $\gtrsim$ 100 MeV gamma ray emission measured with *COS-B*, then $g = 1.08$, a difference of about 30% (Skibo 1993).

We now argue that, if the continuum below $\sim$ 100 keV is of diffuse origin then it is predominantly bremsstrahlung as opposed to inverse Compton emission. To Compton upscatter photons from the cosmic microwave background to energies $\sim$ 100 keV requires electrons of energy about 10 GeV. Upscattering starlight photons to $\sim$ 100 keV requires only $\sim$ 100 MeV electrons. Hence, for the gamma ray emission to turn up below a few hundred keV, the electron spectrum must turn up somewhere between 100 MeV and 10 GeV. Electrons at these energies are responsible for producing the Galactic synchrotron radio emission at frequencies $\sim$ 100 MHz. However, the radio spectrum is observed to break at $\sim$ 100 MHz in the opposite sense (e.g. Berezinskii et al. 1990) to that of the gamma ray emission, making it difficult to reconcile an inverse Compton origin.

One possible, albeit contrived, way around this is to turn up the electron spectrum below 100 MeV in the vicinity of regions of intense ambient UV radiation. For typical interstellar magnetic fields of about 3 $\mu$Gauss such electrons will radiate at frequencies $\lesssim$ 1 MHz well below the Galactic free-free absorption cut off, hence the radio emission will be hidden. Furthermore, to suppress the bremsstrahlung produced by these electrons the environments should have an ambient radiation to gas density that exceeds that of the local ISM by about the factor $10^7$. For these reasons we find that the bremsstrahlung interpretation is the most natural if the emission is truly of diffuse origin. However, as we show in the next section, due to the large power requirement it is possible that the continuum is not of diffuse origin but rather the superposition of unresolved hard X-ray point sources, such as accreting neutron stars or black holes.

## 3. ISM Energetics

We calculate the total power input into the Galaxy by electrons in the energy range spanning 10 keV to 100 keV:

$$\dot{W} = \int_{10\text{keV}}^{100\text{keV}} dE\,E\,\frac{dN_e}{dt\,dE}(E) \simeq 10^{43} \quad (\text{erg s}^{-1}) \quad (7)$$
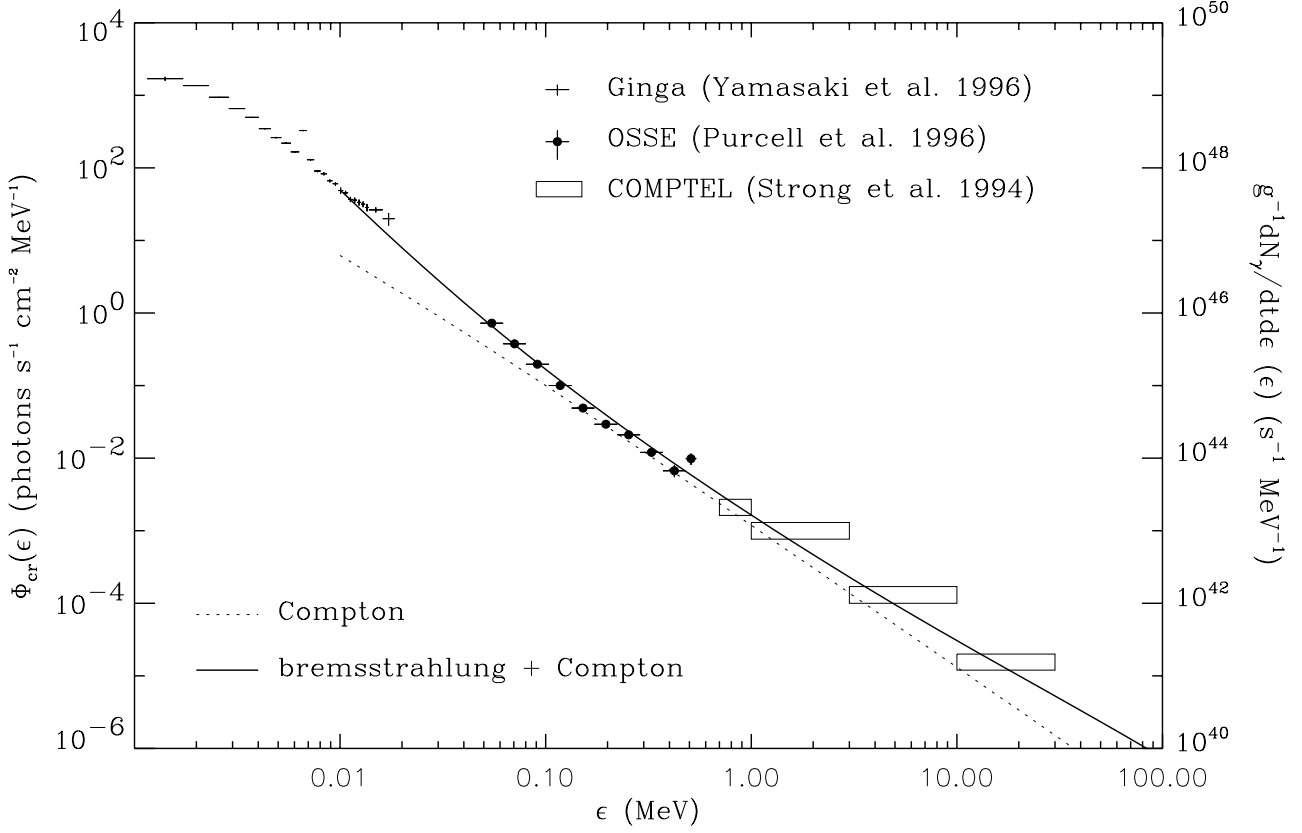
**Fig. 1.** Measurements of the flux from the the central radian of the Galaxy. The OSSE data are the fluxes measured from the Galactic plane at $\ell = 25°$ and $\ell = 339°$ scaled to the central radian. The dotted curve is the contribution from inverse Compton interactions of $\gtrsim$ GeV electrons. The solid curve is the sum of the inverse Compton emission and the bremsstrahlung calculated from the electron source spectrum given in the text. Scaling the central radian flux to the total Galactic luminosity, $dN_\gamma/dt\,d\epsilon$, requires multiplying $\Phi_{cr}$ by the factor $10^{46}g$ where $g$ is of order unity and depends weakly on the unknown Galactic spatial distribution of the emission.

This power is deposited into the ISM and is distributed over the neutral and ionized components as follows. Let $f_i(E, x)$ be the fraction of energy that an electron initially of energy $E$ loses to the ionized portion of the ISM with ionization fraction $x$. It is given by the equation

$$f_i(E, x) = \frac{1}{E} \int_0^E dE' \frac{x\left|\frac{dE}{dt}(E')\right|_i}{x\left|\frac{dE}{dt}(E')\right|_i + (1 - x)\left|\frac{dE}{dt}(E')\right|_n}. (8)$$

We evaluate this integral numerically for $x = 0.047$ using equations (2)-(5) and find that $f_i(E, x)$ varies slowly with $E$, ranging from 0.13-0.18 for 10 keV $\leq E \leq$ 100 keV. We accept a small error and set $f_i \simeq 0.15$ in what follows.

For obtaining estimates of average quantities we employ the approximation that the ISM is homogeneous which is equivalent to the assumption that the electrons permeate all phases of the ISM. The average Galactic ionization rate is then given by

$$\zeta = \frac{(1 - f_i)m_p\dot{W}}{(1 - x)M_{ISM}\bar{\epsilon}_i} \tag{9}$$

where $M_{ISM} \simeq 8 \times 10^9$ M$_\odot$ is the total mass of the ISM (Zombeck 1990) and $\bar{\epsilon}_i \simeq 36$ eV is the mean energy required of a fast particle to produce an electron-ion pair (Dalgarno & Griffing 1959). We obtain $\zeta = 1.6 \times 10^{-14}$ s$^{-1}$. This is easily shown to be an excessive amount of ionization. Equilibrium between ionization and recombination is expressed by the equation

$$(1 - x)\zeta n_H = \alpha x n_H n_e, \tag{10}$$

where $\alpha \simeq 10^{-11}(T/100\mathrm{K})^{-0.7}$ cm$^3$ s$^{-1}$ is the effective recombination coefficient for hydrogen (Bates & Dalgarno 1962). Combining equations (9) and (10) we get

$$x = \sqrt{\frac{(1-f_i)m_p \dot{W}}{\alpha \bar{\epsilon}_i n_H M_{ISM}}} \qquad (11)$$

The temperature and density averaged over the three components of the ISM in the model of McKee & Ostriker (1977) are $T \simeq 2000\mathrm{K}$ and $n_H = n_{HI} + n_{HII} \simeq 1$ cm$^{-3}$ from which we obtain a Galactic average ionization fraction of about 10%, too large by a only factor of two. However, in molecular clouds this corresponds to an ionization fraction $\sim 1\%$ which results in excessive molecular dissociation. We estimate that for every ionization in molecular hydrogen 1.4 H$_2$ molecules are dissociated (Cravens & Dalgarno 1978). Hence, dissociation equilibrium requires

$$2.8\zeta n(H_2) = R n_H n(HI) \qquad (12)$$

where $R = 2 \times 10^{-17}$ cm$^3$ s$^{-1}$ is the H$_2$ formation constant (Spitzer 1978). Again using the average ISM values we obtain $n(H_2)/n(HI) \simeq 5 \times 10^{-4}$ far lower than the Galactic average if molecular hydrogen constitutes a sizable fraction of the mass of the ISM.

## 4. Discussion

A bremsstrahlung origin might be reconcilable in the following way. Suppose the electrons only temporarily borrow their power from Galactic spiral density waves. In a period of about 100 Myr on average the entire Galaxy will flow through a density wave. This has the effect of compressing and decompressing the Galaxy by a factor of 2-5, though not all at once, temporarily making available the required $10^{43}$ erg s$^{-1}$. Furthermore, a weak shock forms as the ISM flows through such waves. Thus, a possible scenario involves the acceleration of the electrons in the weak shock resulting in a steep source spectrum as required. Furthermore, suppose the electrons are excluded from the clouds (Strong et al. 1994) and preferentially deposit their energy down stream into the intercloud medium. Then excessive dissociation of interstellar molecules will be avoided, and the heat will be stored in the hot ($10^6$ K) gas. This gas then cools predominately through adiabatic expansion, not radiatively, as it flows out of the density wave. At the end of the cycle the energy is back in the form of gravitational potential. A similar scenario has been invoked to explain the origin of the synchrotron emitting electrons in NGC 3310 (Duric 1986).

On the other hand, the problems with the energetics are considerably mitigated if the continuum emission is not of diffuse origin but instead a superposition of hard X-ray point sources such as accreting neutron stars or black holes. In these sources the emission is most likely due to thermal Comptonization which would require much less power in aggregate. Furthermore, the spectrum in Fig. 1 seems to suggest the presence of an albedo hump (Lightman & White 1988) between $\sim$ 10 - a few hundred keV, such as that seen in the spectra of individual Galactic and extragalactic black hole sources and attributed to reflection of the primary continuum off an accretion disk (Done et al. 1992; Mushotsky, Done, & Pounds 1993).

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